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(54) Title: ANTIBODY FRAGMENT–TARGETED IMMUNOLIPOSOMES FOR SYSTEMIC GENE DELIVERY

(57) Abstract

    Nucleic acid–immunoliposome compositions useful as therapeutic agents are disclosed. These compositions preferably comprise (i) cationic liposomes, (ii) a single chain antibody fragment which binds to a transferrin receptor, and (iii) a nucleic acid encoding a wild type p53. These compositions target cells which express transferrin receptors, e.g., cancer cells. These compositions can be used therapeutically to treat persons or animals who have cancer, e.g., head and neck cancer, breast cancer or prostate cancer.

TITLE OF THE INVENTION

ANTIBODY FRAGMENT-TARGETED IMMUNOLIPOSOMES FOR SYSTEMIC GENE
DELIVERY

5   BACKGROUND OF THE INVENTION

This invention provides methods for the preparation of antibody fragment-targeted
liposomes ("immunoliposomes"), including lipid-tagged antibody fragment-targeted liposomes,
methods for *in vitro* transfection using the immunoliposomes, and methods for systemic gene
delivery *in vivo*. The liposomes of the present invention are useful for carrying out targeted gene
10   delivery and efficient gene expression after systemic administration. The specificity of the
delivery system is derived from the targeting antibody fragments.

An ideal therapeutic for cancer would be one that selectively targets a cellular pathway
responsible for the tumor phenotype and which is nontoxic to normal cells. While cancer
treatments involving gene therapy have substantial promise, there are many issues that need to
15   be addressed before this promise can be realized. Perhaps foremost among the issues associated
with macromolecular treatments is the efficient delivery of the therapeutic molecules to the
site(s) in the body where they are needed. A variety of delivery systems (a.k.a. "vectors") have
been tried including viruses and liposomes. The ideal delivery vehicle would be one that could
be systemically (as opposed to locally) administered and which would thereafter selectively target
20   tumor cells wherever they occur in the body.

The infectivity that makes viruses attractive as delivery vectors also poses their greatest
drawback. Consequently, a significant amount of attention has been directed towards non-viral
vectors for the delivery of molecular therapeutics. The liposome approach offers a number of
advantages over viral methodologies for gene delivery. Most significantly, since liposomes are
25   not infectious agents capable of self-replication, they pose no risk of transmission to other
individuals. Targeting cancer cells via liposomes can be achieved by modifying the liposomes
so that they selectively deliver their contents to tumor cells. There now exists a significant
knowledge base regarding specific molecules that reside on the exterior surfaces of certain cancer
cells. Such cell surface molecules can be used to target liposomes to tumor cells, because the
30   molecules that reside upon the exterior of tumor cells differ from those on normal cells.

The publications and other materials used herein to illuminate the background of the
invention or provide additional details respecting the practice, are incorporated by reference.

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Current somatic gene therapy approaches employ either viral or non-viral vector systems. Many viral vectors allow high gene transfer efficiency but are deficient in certain areas (Ledley FD, et al. *Hum. Gene Ther.* (1995) 6:1129-1144). Non-viral gene transfer vectors circumvent some of the problems associated with using viral vectors. Progress has been made toward developing non-viral, pharmaceutical formulations of genes for *in vivo* human therapy, particularly cationic liposome-mediated gene transfer systems (Massing U, et al., *Int. J. Clin. Pharmacol. Ther.* (1997) 35:87-90). Features of cationic liposomes that make them versatile and attractive for DNA delivery include: simplicity of preparation; the ability to complex large amounts of DNA; versatility in use with any type and size of DNA or RNA; the ability to transfect many different types of cells, including non-dividing cells; and lack of immunogenicity or biohazardous activity (Felgner PL, et al., *Ann. NY Acad. Sci.* (1995) 772:126-139; Lewis JG, et al., *Proc. Natl. Acad. Sci. USA* (1996) 93:3176-3181). More importantly from the perspective of human cancer therapy, cationic liposomes have been proven to be safe and efficient for *in vivo* gene delivery (Aoki K et al., *Cancer Res.* (1997) 55:3810-3816; Thierry AR, *Proc. Natl. Acad. Sci. USA* (1997) 92:9742-9746). More than thirty clinical trials are now underway using cationic liposomes for gene therapy (Zhang W et al., *Adv. Pharmacology* (1997) 32:289-333; RAC Committee Report: Human Gene Therapy Protocols-December 1998), and liposomes for delivery of small molecule therapeutics (e.g., antifungal and conventional chemotherapeutic agents) are already on the market (Allen TM, et al., *Drugs* (1997) **54 Suppl 4**:8-14).

The transfection efficiency of cationic liposomes can be dramatically increased when they bear a ligand recognized by a cell surface receptor. Receptor-mediated endocytosis represents a highly efficient internalization pathway present in eukaryotic surface (Cristiano RJ, et al., *Cancer Gene Ther.* (1996) 3:49-57, Cheng PW, *Hum. Gene Ther.* (1996) 7:275-282). The presence of a ligand on a liposome facilitates the entry of DNA into cells through initial binding of ligand by its receptor on the cell surface followed by internalization of the bound complex. A variety of ligands have been examined for their liposome-targeting ability, including transferrin and folate (Lee RJ, et al., *J. Biol. Chem.* (1996) 271:8481-8487). Transferrin receptors (TfR) levels are elevated in various types of cancer cells including prostate cancers, even those prostate cell lines derived from human lymph node and bone metastases (Keer HN et al., *J. Urol.* (1990) 143:381-385); Chackal-Roy M et al., *J. Clin. Invest.* (1989) 84:43-50; Rossi MC, et al., *Proc. Natl. Acad. Sci. USA* (1992) 89:6197-6201; Grayhack JT, et al., *J. Urol.* (1979) 121:295-299).

Elevated TfR levels also correlate with the aggressive or proliferative ability of tumor cells (Elliot RL, et al., *Ann. NY Acad. Sci.* (1993) **698**:159-166). Therefore, TfR levels are considered to be useful as a prognostic tumor marker, and TfR is a potential target for drug delivery in the therapy of malignant cells (Miyamoto T, et al., *Int. J. Oral Maxillofac. Surg.* (1994) **23**:430-433:,

5   Thorstensen K, et al., *Scand. J. Clin. Lab. Invest. Suppl.* (1993) **215**:113-120). In our laboratory, we have prepared transferrin-complexed cationic liposomes with tumor cell transfection efficiencies in SCCHN of 60%-70%, as compared to only 5-20% by cationic liposomes without ligand (Xu L. et al., *Hum. Gene Ther.* (1997) **8**:467-475).

In addition to the use of ligands that are recognized by receptors on tumor cells, specific

10   antibodies can also be attached to the liposome surface (Allen TM et al., (1995) <u>Stealth Liposomes</u>, pp. 233-244) enabling them to be directed to specific tumor surface antigens (including but not limited to receptors) (Allen TM, *Biochim. Biophys. Acta* (1995) **1237**:99-108). These "immunoliposomes," especially the sterically stabilized immunoliposomes, can deliver therapeutic drugs to a specific target cell population (Allen TM, et al., (1995) <u>Stealth Liposomes</u>,

15   pp. 233-244). Park, et al. (Park JW, et al., *Proc. Natl. Acad. Sci. USA* (1995) **92**:1327-1331) found that anti-HER-2 monoclonal antibody (Mab) Fab fragments conjugated to liposomes could bind specifically to HER-2 overexpressing breast cancer cell line SK-BR-3. The immunoliposomes were found to be internalized efficiently by receptor-mediated endocytosis via the coated pit pathway and also possibly by membrane fusion. Moreover, the anchoring of

20   anti-HER-2 Fab fragments enhanced their inhibitory effects. Doxorubicin-loaded anti-HER-2 immunoliposomes also showed significant and specific cytotoxicity against target cells *in vitro* and *in vivo* (Park JW, et al., *Proc. Natl. Acad. Sci. USA* (1995) **92**:1327-1331). In addition, Suzuki et al., (Suzuki S, et al., *Br. J. Cancer* (1997) **76**:83-89) used an anti-transferrin receptor monoclonal antibody conjugated immunoliposome to deliver doxorubicin more effectively in

25   human leukemia cells *in vitro*. Huwyler et al. (Huwyler J, et al., *Proc. Natl. Acad. Sci. USA* (1996) **93**:14164-14169) used anti-TfR monoclonal antibody immunoliposome to deliver daunomycin to rat glioma (RT2) cells *in vivo*. This PEGylated immunoliposome resulted in a lower concentration of the drug in normal tissues and organs. These studies demonstrated the utility of immunoliposomes for tumor-targeting drug delivery. It should be noted that the

30   immunoliposome complexes used by Suzuki et al. and Huwyler et al. differ from those of the

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invention described herein in that they are anionic liposomes and that the methods used by Suzuki et al. and Huwyler et al. are not capable of delivering nucleic acids.

Single-chain antibody fragments

Progress in biotechnology has allowed the derivation of specific recognition domains
5   from Mab (Poon RY, (1997) Biotechnology International: International Developments in the Biotechnology Industry, pp. 113-128). The recombination of the variable regions of heavy and light chains and their integration into a single polypeptide provides the possibility of employing single-chain antibody derivatives (designated scFv) for targeting purposes. Retroviral vectors engineered to display scFv directed against carcinoembryonic antigen, HER-2, CD34, melanoma
10   associated antigen and transferrin receptor have been developed (Jiang A, et al., *J. Virol.* (1998) 72:10148-10156, Konishi H, et al., *Hum. Gene Ther.* (1994) 9:235-248:, Martin F, et al., *Hum. Gene Ther.* (1998) 9:737-746). These scFv directed viruses have been shown to target, bind to and infect specifically the cell types expressing the particular antigen. Moreover, at least in the case of the carcinoembryonic antigen, scFv was shown to have the same cellular specificity as
15   the parental antibody (Nicholson IC, *Mol. Immunol.* (1997) 34:1157-1165).

The combination of cationic liposome-gene transfer and immunoliposome techniques appears to be a promising system for targeted gene delivery.

SUMMARY OF THE INVENTION

20   We constructed a variety of immunoliposomes that are capable of tumor-targeted, systemic delivery of nucleic acids for use in human gene therapy. Based upon the data given in the Examples below these immunoliposome-DNA complexes incorporating the TfRscFv are capable of producing a much higher level of transfection efficiency than the same liposome-DNA complex bearing the complete Tf molecule. Therefore, in one aspect of the invention the
25   immunoliposomes of the invention can be used to produce a kit for high efficiency transfection of various mammalian cell types that express the transferrin receptor. In one aspect of the invention, we constructed an scFv protein with a lipid tag such that the lipid is added naturally by the bacterial cell to allow easy incorporation of the scFv into liposomes while also avoiding chemical reactions which can inactivate the scFv.

30   The lipid-tagged scFv-immunoliposomes are prepared basically by two methods: a lipid-film solubilization method and a direct anchoring method. The lipid-film solubilization

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method is modified from the detergent dialysis method, which was described by Laukkanen ML, et al., (Laukkanen ML, et al., *Biochemistry* (1994) **33**:11664-11670) and de Kruif et al., (de Kruif et al., *FEBS Lett.* (1996) **399**:232-236) for neutral or anionic liposomes, with the methods of both hereby incorporated by reference. This method is suitable for attaching lipid-tagged scFv to

5   cationic liposomes as well. In the lipid-film solubilization method, the lipids in chloroform are evaporated under reduced pressure to obtain a dry lipid film in a glass round-bottom flask. The lipid film is then solubilized with 0.5-4%, preferably 1%, n-octyl β-D-glucoside (OG) containing the lipid-modified scFv and vortexed. After dilution with sterile water, the solution is briefly sonicated to clarity.

10   The second method for attaching lipid-tagged antibodies or antibody fragments is the direct anchoring method that is specifically useful for attaching the *E. coli* lipoprotein N-terminal 9 amino acids to an scFv (lpp-scFv) or other lipid-modified antibody or fragments and attaching these to preformed liposomes. For attaching the scFv to preformed liposomes, the lipid-modified scFv in 1% OG is added to preformed liposomes while vortexing, at volume ratios from 1:3 to

15   1:10. The mixture is vortexed for approximately a further 5-10 minutes to obtain a clear solution of scFv-immunoliposomes. The remaining OG and the uncomplexed scFv can be eliminated by chromatography, although they will not interfere very much with the subsequent usage. Separation experiments, i.e., ultrafiltration with Centricon-100 (Amicon), Ficoll-400 floatation (Shen DF, et al., *Biochim. Biophys. Acta* (1982) **689**: 31-37), or Sepharose CL-4B (Pharmacia)

20   chromatography, demonstrated that virtually all the lipid-tagged scFv molecules added have been attached or anchored to the cationic liposomes. This is an improvement over the much lower attachment rate of lpp-scFv to neutral or anionic liposomes. Therefore, this improvement makes it unnecessary to include a further purification step to remove the unattached scFv.

         Any antibodies, antibody fragments, or other peptide/protein ligands that can be modified

25   to have one or more lipid-tags on the surface are useful in the present invention. Other lipid-modification methods include directly conjugating a lipid chain to an antibody or fragment, as described in Liposome Technology, 2nd Ed., Gregoriadis, G., Ed., CRC Press, Boca Raton, FL, 1992.

         In another aspect of the invention a cysteine was added at the C-terminus of the scFv

30   sequence and the protein was expressed in the inclusion bodies of *E. coli*, then refolded to produce active scFv. The C-terminal cysteine provided a free sulfhydryl group to facilitate the

conjugation of the scFv to liposomes. There are two strategies which can be used in the conjugation process. 1) Pre-linking method: The first step is to conjugate the scFv-SH with the cationic liposome which contains a maleimidyl group or other sulfhydryl-reacting group, to make the scFv-liposome. The nucleic acids are then added to the scFv-liposome to form the scFv-liposome-DNA complex. The pre-linking is designated since scFv is linked before DNA complexing. 2) Post-linking method: This strategy is to complex the cationic liposome with nucleic acids first to form a condensed structure. The scFv-SH is then linked onto the surface of DNA-liposome complex to produce scFv-liposome-DNA. The post-linking is designated since scFv is linked after DNA complexing. The post-linking strategy ensures that 100% of scFv linked are on the surface of the complex, accessible to receptor binding. Therefore, this method can make a better use of the targeting ligand scFv and a better controlled inside structure of the complex.

The nucleic acid-immunoliposome complexes, regardless of whether the antibody or antibody fragment is lipid tagged or conjugated to the liposome, can be used therapeutically. Preferably the complexes are targeted to a site of interest, preferably to a cell which is a cancer cell, more preferably to a cell expressing a transferrin receptor. The targeting agent is the antibody or antibody fragment which preferably binds to a transferrin receptor. The nucleic acid is the therapeutic agent and is preferably a DNA molecule and more preferably encodes a wild type p53 molecule. The nucleic acid-immunoliposome complexes, preferably in a therapeutic composition, can be administered systemically, preferably intravenously.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 show scFv TfR lipid-tag construction.

Figure 2 shows a Western blot analysis of scFv-liposome-targeted p53 expression *in vivo* in tumor xenografts with systemic administration.

Figure 3 shows pCMVp53 and pCMVpRO constructs.

Figure 4 shows p53-3'Ad construction.

Figure 5 shows construction of scFvTfR-cysteine with a His tag.

Figure 6 shows construction of scFvTfR-cysteine without a His tag.

Figure 7 shows construction of scFvTfR-cysteine with a cellulose binding domain (CBD) tag and with an S-tag.

Figure 8 shows a Coomassie Blue stained SDS-polyacrylamide gel of purified TfRscFv protein produced by the conjugation method.

Figure 9 shows a Western blot analysis of conjugation method produced TfRscFv-liposome-targeted p53 expression *in vivo* in tumor xenografts with systemic administration.

DETAILED DESCRIPTION OF THE INVENTION

The invention is directed to immunoliposomes and methods of making and using these immunoliposomes. A variety of embodiments are disclosed including immunoliposomes with different tags and various methods with which to attach the scFv to the liposomes. The immunoliposomes may include lipid tags or be linked through a reducing group, which in a preferred embodiment is a free sulfhydryl.

Mutant forms of the tumor suppressor gene p53 have been associated with more than 50% of human cancers, including 15-50% of breast and 25-70% of metastatic prostate cancers. Abnormalities in p53 also correlate with poor prognosis in various types of malignancies. Therefore, the capability to systemically deliver and target gene therapy specifically to tumors to efficiently restore wtp53 function will be an important therapeutic modality in cancer treatment. Thus the immunoliposomes produced by the method of this invention will be useful as an effective new cancer therapeutic modality not just for restoration of wtp53 function but also as a tumor targeted systemic delivery vehicle for other therapeutic genes.

The invention is illustrated by the following Examples.

Example 1

Construction and Expression of Biosynthetically Lipid-tagged scFv

1. Construction of the Expression Vector for TfRscFv

To construct the expression vector, we used the vector pLP1 which contains an amino acid linker sequence between the *E. coli* lipoprotein signal peptide (ssLPP) and the scFv cloning site (de Kruif et al., *FEBS Lett.* (1996) **399**:232-236). This vector contains both c-myc and His_6 tag sequences that can be used for purification and detection of the expressed scFv (Figure 1).

We obtained a plasmid expression vector, pDFH2T-vecOK, which contains the single chain fragment for the 5E9 (Haynes et al., *J. Immunol.* (1981) **127**:347-351) antibody linked to a DNA binding protein, which recognizes the human transferrin receptor (TfR). This vector also

contains the sequence for a DNA binding protein, and there are no unique restriction enzyme sites flanking the scFv sequence in pDFH2T-vecOK. Therefore, we cloned the VH-linker-Vκ scFv by PCR amplification of the desired fragment using a 5' primer (5' GGCCCATGGAGGTGCAGCTGGTGG 3' (SEQ ID NO:1)) (RB551) containing an *NcoI* site and a 3' primer (RB552) (5' CCGGAATTCGCGGCCGCTTTTATCTCCAGCTTGGTC 3' (SEQ ID NO:2) containing a *NotI* site. The PCR amplification using primers RB551 and RB552 amplified the scFv for TfR from pDFH2T-vecOK from the Met at base 81 to Lys at base 821. The pLP1 vector also contains sequences for the *E. coli* lipoprotein signal peptide (ssLPP) and the *E. coli* lipoprotein N-terminal 9 amino acids (LPP), as described by Laukkanen ML, et al., (Laukkanen ML, et al., *Biochemistry* (1994) **33**:11664-11670) and de Kruif et al (de Kruif et al., *FEBS Lett.* (1996) **399**:232-236). The insertion of these sequences will lead to fatty acid acylation of the expressed signal in the *E. coli* host and its insertion into the bacterial membrane. The vector also has a non-critical 10 amino acid linker sequence to increase the space between the lipid-tag site and the scFv. Purification of the lipid modified scFv sequence from the bacterial membrane results in an active molecule that can be attached or inserted into liposomes.

2.   Expression and Purification of the TfRscFv

We transformed *E. coli* expression host SF110 F' with the expression vector constructed above. While the host cell is not critical it is preferred that it contain expressed lac repressor. A number of clones were selected and the one that produces the best yield of scFv was chosen. The lipid-modified scFv (lpp-scFv) was isolated from the bacterial membrane using Triton X-100 as described by de Kruif et al., (de Kruif et al., *FEBS Lett.* (1996) **399**:232-236). For purification a single colony was resuspended in 200 μl LB containing 5% glucose and the appropriate antibiotics. The mixture was plated onto two 90 mm LB agar plates containing 5% glucose and the appropriate antibiotics and grown overnight. The next day, the cells were washed from the plates and used to inoculate a total of 5 liters of LB containing 0.1% glucose and the appropriate antibiotics. The cultures were grown at 25°C, at 200 rpm for 6 hours until the OD_{600} reached 0.5 to 0.7. IPTG was added to a final concentration of 1 mM and the cultures were further incubated overnight. The next day, the bacterial cultures were collected by centrifugation and lysed in 200 ml lysis buffer at room temperature for 30 minutes. The sample was sonicated at 28 watts for 5 minutes with cooling on ice. The lysis buffer contains 20 mM HEPES pH 7.4 to 7.9, 0.5 M

NaCl, 10% glycerol, and 0.1 mM PMSF. The only deviations from the cited protocol include washing and elution of metal affinity columns in buffer containing 20 mM HEPES pH 7.4 to 7.9, 0.5 M NaCl, 10% glycerol, 0.1 mM PMSF, 1% n-octyl β-D-glucoside (OG), and 10% glycerol containing 20 and 200 mM imidazole, respectively. The eluted samples of lpp-scFv were analyzed by SDS-PAGE and Western Blot using anti-c-myc antibody 9E10 which confirmed that the purified scFv showed a band of the size of about 30 kDa.

Example 2

Preparation of Lipid-tagged
scFv-immunoliposomes by a Lipid-film Solubilization Method

This example discloses a detailed procedure of lipid-film solubilization method to prepare lipid-tagged scFv-immunoliposomes. 5 μmol lipids (DOTAP/DOPE, 1:1 molar ratio) in chloroform are evaporated under reduced pressure to obtain a dry lipid film in a glass round-bottom flask. To the lipid film is added 0.5 ml 1% OG, 20 mM HEPES, 150 mM NaCl, pH 7.4, containing the lipid-modified scFv. This is incubated 10-20 minutes at room temperature and then vortexed to solubilize the lipid membrane. 2 ml sterile water is then added to dilute the scFv-lipid mixture. The solution is briefly sonicated to clarity in a bath-type sonicator at 20°C. The scFv-liposome is a clear solution with a limited amount of detergent OG left. The OG and the uncomplexed scFv can be eliminated by chromatography with Sepharose CL-4B or Sephacryl S500, even though they do not interfere a lot with the subsequent use.

Example 3

Preparation of Lipid-tagged
scFv-immunoliposomes by a Direct Anchoring Method

This example provides a direct anchoring method to prepare lipid-tagged scFv-immunoliposomes. 20 μmol lipids (LipA-H, see below for compositions and ratios) prepared as dry lipid film in a glass round-bottom flask is added to 10 ml pure water and sonicated in a bath-type sonicator for 10-30 min at room temperature (LipA, B, C) or at 65°C (LipD, E, G, H, or any composition with Cholesterol (Chol)). The cationic liposomes prepared are clear solutions, their compositions and ratios are as follows:

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LipA	DOTAP/DOPE	1:1 molar ratio
LipB	DDAB/DOPE	1:1 molar ratio
LipC	DDAB/DOPE	1:2 molar ratio
LipD	DOTAP/Chol	1:1 molar ratio
LipE	DDAB/Chol	1:1 molar ratio
LipG	DOTAP/DOPE/Chol	2:1:1 molar ratio
LipH	DDAB/DOPE/Chol	2:1:1 molar ratio

For attaching the scFv to preformed liposomes, the lipid-modified scFv (lpp-scFv) in 20 mM HEPES, 150 mM NaCl, pH 7.4, containing 1% OG is added to preformed liposomes while vortexing, at volume ratios from 1:3 to 1:10. The mixture is vortexed for a further 1 to 5 min to get a clear solution of scFv-immunoliposomes. The remaining OG and the uncomplexed scFv can be eliminated by chromatography, although they do not interfere very much with the subsequent usage. Separation experiments, i.e., ultrafiltration with Centricon-100 (Amicon), Ficoll-400 floatation (Shen DF, et al., *Biochim Biophys Acta* (1982) **689**:31-37), or Sepharose CL-4B (Pharmacia) chromatography, demonstrated that virtually all the lipid-tagged scFv added have been attached or anchored to the cationic liposomes. This is in contrast to the much lower attachment rate of lpp-scFv to neutral or anionic liposomes. Therefore, it is unnecessary to have a further purification step to get rid of the unattached scFv.

Example 4

Immunoreactivity of Lipid-tagged scFv-

immunoliposomes Revealed by ELISA, FACS and Immunofluorescence

This example provides the characterization of the anti-TfR scFv-immunoliposomes with respect to their ability of binding to the TfR(+) cells. The human prostate cancer cell line DU145 and the human squamous cell carcinoma of head and neck cell line JSQ-3 served as the TfR+ target cells for these studies.

Indirect cellular enzyme-linked immunosorbent assay (ELISA) was employed to determine the immunoreactivity of the lpp-scFv before and after attachment to liposomes. Confluent JSQ-3 cells in 96-well plates were fixed with 0.5% glutaraldehyde in PBS for 10 min at room temperature. The plate was blocked with 5% fetal bovine serum (FBS) in PBS at 30°C

for 30 min. The lpp-scFv, scFv-immunoliposomes and liposomes were added to wells in duplicate and incubated at 4°C overnight. After three PBS-washes, an anti-c-myc monoclonal antibody was added to each well in 3% FBS in PBS and incubated at 37°C for 60 min. After three PBS-washes, HRP-labeled goat-anti-mouse IgG (Sigma) diluted in 3% FBS was added to each well and incubated for 30 min at 37°C. The plate was washed three times with PBS and 100 μl substrate 0.4 mg/ml OPD in citrate phosphate buffer (Sigma) was added to each well. The color-development was stopped by adding 100 μl 2 M sulfuric acid to each well. The plate was read by an ELISA plate reader (Molecular Devices Corp.) at 490 nm. Indirect cellular ELISA demonstrated that the anti-TfR scFv retained its immunoreactivity after incorporation into the liposome complex (Table 1).

Table 1

Binding of anti-TfR scFv-liposomes to JSQ-3 cells*

Lip(A) only	0.142 ± 0.036
scFv-LipA1	1.134 ± 0.038
scFv-LipA2	1.386 ± 0.004
lpp-scFv	0.766 ± 0.009

* ELISA, OD_{490}, Mean ± SD

scFv-LipA1: by lipid-film solubilization method.

scFv-LipA2: by direct anchoring method.

For FACS analysis, anti-TfR scFv-Lip(A), was incubated at 4°C with JSQ-3 and DU145 cells, then with FITC-labeled sheep anti-mouse IgG, also at 4°C. Incubation of JSQ-3 cells with the scFv-Lip(A) resulted in a fluorescence shift identical to that observed with the unattached free anti-TfR lpp-scFv antibody, demonstrating a significant amount of binding to the target cells. In contrast, the untargeted liposome demonstrated very low binding to the cells. Similar results were observed with prostate tumor cell line DU145. Here also, the scFv-Lip(A) complex demonstrated clear, substantial binding to the tumor cells, as compared to the untargeted Lip(A). The FACS data is summarized in Table 2, where the fluorescence shift is indicated as the percent of the cells displaying fluorescence above the threshold level (percent of positive cells). In these studies also, the level of binding to the cells, represented by the percent of positive cells, was

similar to that of the unattached free scFv further indicating that incorporation into the liposome complex did not inactivate the immunological activity of the anti-TfR lpp-scFv. It should be noted that the liposome preparation used for these initial experiments with DU145 was that optimized for JSQ-3 cells. Therefore, the binding of the scFv-targeted liposome complex to the prostate tumor cells can be further enhanced by the use of the liposome complex optimized for this cell type.

Table 2

FACS Analysis of TfRscFv-liposome Binding to JSQ-3 and DU145

	JSQ-3		DU145	
Transfected by	% Positive	Mean[a]	% Positive	Mean[a]
Untransfected	3.46	4.07	2.22	3.40
Lip(A)	9.69	6.26	4.51	4.07
scFv-LipA1	86.38	19.8	50.19	12.40
scFv-LipA2	89.58	21.30	39.52	11.1
Free lpp-scFv	85.09	21.30	78.09	18.40
HB21[b]	99.44	69.80	98.70	64.90

a: Mean of the relative fluorescence

b: Parental monoclonal antibody of the anti-TfR scFv

Indirect immunofluorescence staining with scFv-liposome (where Lip(A) had been labeled with rhodamine-DOPE) and FITC-labeled anti-mouse IgG following anti-c-myc antibody, confirmed the binding of the scFv-targeted liposome complex to the JSQ-3 cells. The concurrence of the red and green fluorescence in the transfected cells demonstrates that the anti-TfR scFv (indicated by the FITC-labeled anti-c-myc antibody as green fluorescence) does indeed direct the rhodamine-labeled Lip(A) to the cells. Moreover, the high level of cellular binding of the scFv-Lip(A) system is demonstrated by the large percentage of red/green double-positive fluorescent cells.

13

Example 5

Optimization of scFv-immunoliposome

Mediated Gene Transfection of Target Cells *In Vitro*

We determined the *in vitro* transfection efficiency of the anti-TfR scFv-Lip(A) complex

5   in JSQ-3 cells using β-galactosidase as the reporter gene. In these studies the reporter construct

used contained the β-galactosidase gene under the control of the CMV promoter (pCMVb), the

same promoter used in pCMVp53 (Figure 3). The level of β-Gal expression in the transfected

cells (correlating with the transfection efficiency) was assessed by β-Gal enzymatic assay (Xu

L, et al., *Hum. Gene Ther.* (1997) 8:467-475). As shown in Table 3, the attachment of the

10   anti-TfR scFv to the Lip(A) resulted in a doubling of the enzyme activity in the

scFv-Lip(A)-pCMVb transfected cells, as compared to the untargeted liposome complex. This

level of expression was also found to be virtually identical to that observed when transferrin itself

was used as the targeting ligand (Tf-Lip(A)-pCMVb). Moreover, this increase in gene expression

was shown to be reporter gene DNA dose dependent. Table 4 shows the optimization of

15   scFv-liposome mediated transfection of JSQ-3 cells.

Table 3

Transfection of JSQ-3 Cells by Anti-TfR scFv-liposomes*

DNA (µg/well)	Lip(A) only	Tf-Lip(A)	scFV-LipA1	scFv-LipA2
1.0	475	1031	997	1221
0.5	601	981	811	854
0.25	266	503	578	471
0.125	130	262	215	236

* milliunits/mg protein, β-galactosidase equivalent, β-Gal enzymatic assay

25   scFv-LipA1: by lipid-film solubilization method

scFv-LipA2: by direct anchoring method

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Table 4

Optimization of scFv-liposome transfection to JSQ-3*

DNA/Lip (μg/nmol)	Lip(A) only	scFv-LipA1	scFv-LipA2	scFv-LipB	scFv-LipD	scFv-LipG
1/8	1.559	2.793	2.642	1.827	0.874	0.648
1/10	1.776	2.846	2.83	2.268	1.606	1.283
1/12	1.868	2.772	2.815	2.175	1.257	1.416
1/14	1.451	3.031	2.797	2.31	1.78	1.656

* β-Gal enzymatic assay, OD_{405}

scFv-LipA1: by lipid-film solubilization method

scFv-LipA2: by direct anchoring method

Example 6

scFv-immunoliposome Mediated p53 Gene Transfection

Target to Tumor Cells Causing Sensitization to Chemotherapeutic Agents

1.   Anti-TfR scFv Facilitated Liposome-Mediated wtp53 Gene Transfection *In Vitro*

The expression of exogenous wtp53 in JSQ-3 tumor cells transfected with the anti-TfR scFv-targeted Lip(A)-p53-3'Ad was assessed by co-transfection of an expression plasmid (pBP100) which contains the luciferase reporter gene under the control of a p53 responsive promoter (Chen L, et al., *Proc. Natl. Acad. Sci. USA* (1998) 95:195-200). Consequently, the higher the level of exogenous wt p53 expression (representing the scFv-Lip(A)-p53-3'Ad transfection efficiency), the higher the level of luciferase activity. This luciferase enzyme activity is expressed as relative light units (RLU). As was demonstrated above with the β-gal reporter gene, the addition of the anti-TfR scFv as the targeting agent to the Lip(A)-p53-3'Ad complex resulted in a significant increase in transfection efficiency and wtp53 protein expression (as expressed by RLU of Luciferase activity) over the untargeted Lip(A)-p53-3'Ad complex (Table 5). Once again, the level of p53 expression in the scFv-Lip(A)-p53-3'Ad transfected cells was similar to that observed when transferrin itself was used as the targeting ligand (LipT(A)-p53-3'Ad). Therefore, these findings indicate that the anti-TfR single-chain antibody strategy is a useful method of targeting the cationic liposome complex, and delivering a biologically active wtp53 gene, to tumor cells.

15

Table 5

In Vitro p53 Expression Mediated by Different Liposomes in JSQ-3 cells

Transfected by		RLU*
Medium	+ p53-3'Ad + pBP100	158
Lip(A)	+ p53-3'Ad + pBP100	4073
LipT(A)	+ p53-3'Ad + pBP100	7566
scFv-Lip(A1)	+ p53-3'Ad + pBP100	6441

* Relative light units per well

2.   Anti-TfR scFv-immunoliposome mediated p53 gene restoration sensitized the tumor cells to the cytotoxicity of Cisplatin (CDDP).

For the p53-induced apoptosis study, mouse melanoma cell line B16 was transfected with anti-TfR scFv-immunoliposome complexed with p53-3'Ad (Figure 4) or pCMVpRo plasmid (Figure 3) DNA (scFv-Lip(A)-p53 and scFv-Lip(A)-pRo, respectively) at a dose of 5 μg DNA/2 x 10^5 cells in 2 sets of 6-well plates. For comparison, transferrin-liposome-DNA (LipT-p53 or LipT-pRo) were also transfected at a dose of 5 μg DNA/2 x 10^5 cells. 24 hours later, CDDP was added to one set of plates to 10 μM final concentration. 24 and 48 hours after the drug was added, both the attached and floating cells were collected for apoptosis staining. The cells were stained with an Annexin V-FITC Kit (Trevigen, Inc., Gaithersburg, MD) according to manufacturer's protocol. Annexin V is a lipocortin, a naturally occurring blood protein and anti-coagulant. The stained cells were analyzed on a FACStar cytometer (Becton and Dickinson). Table 6 summarizes the results of the apoptosis analysis.

Table 6

Apoptosis of B16 Cells Induced by Liposomal p53-gene Restoration and CDDP*

Transfected by	24 hours		48 hours	
	- CDDP	+ CDDP	- CDDP	+ CDDP
Untransfected	0.22	4.4	6.33	20.11
LipA-p53	15.9	26.7	15.02	26.52
scFv-LipA-p53	13.9	38.4	34.94	43.7
scFv-LipA-pRo	8.1	19.9	24.14	37.59
Tf-LipA-p53	22.4	29.5	34.47	31.7
Tf-LipA-pRo	14.1	12.6	14.00	25.34

* % of apoptotic cells (Annexin V-FITC positive)

Without CDDP there was no increase in the percent of apoptotic cells induced at 24 hours by the addition of the scFv ligand as compared to the amount induced by the liposome complex alone. However, by 48 hours, there is a greater than 2-fold increase in the percent of apoptotic cells by the addition of the targeting scFv to the lipoplex. With CDDP there is a significant

5   increase in apoptotic cells (approximately 1.5-fold) even at 24 hours as compared to the untargeted liposome complex. More significantly, this increase in apoptotic cells in combination with CDDP is more pronounced using the scFv to the Tf receptor as the targeting ligand than using the Tf molecule itself. This increase correlates with transfection efficiency.

10   Example 7

scFv-immunoliposome-targeted wtp53 Gene

Delivery and Expression *In Vivo* with Systemic Administration

To examine the ability of the anti-TfR scFv containing liposomes to deliver wtp53 specifically to tumor tissue *in vivo*, scFv-Lip(A)-p53-3'Ad (Figure 4) or the untargeted

15   Lip(A)-p53-3'Ad (Figure 4) was injected intravenously into nude mice bearing JSQ-3 subcutaneous xenograft tumors. Two days after injection, the tumors were excised and protein isolated from liver and skin, as well as the tumor, for Western blot analysis (Xu L, et al., *Hum. Gene Ther.* (1997) **8**:467-475). Equal amounts of protein (100 µg, as determined by concentration) were loaded in each lane. As shown in Figure 2, the tumor from the mouse

20   systemically treated with the scFv-Lip(A)-p53-3'Ad complex, labeled scFv-Lip(A)-p53 in Figure 2, displayed a very intense p53 signal as well as the additional lower band indicative of a high level of expression of the exogenous wtp53, while only the lower expression of the endogenous mouse p53 is evident in both the skin and the liver. In contrast, as would be expected based upon our earlier results, a significantly lower level of exogenous p53 expression is evident in the tumor

25   isolated from the untargeted Lip(A)-p53-3'Ad injected mouse, labeled Lip(A)-p53 in Figure 2. Therefore, the liposome complex targeted by our new and unique anti-TfR lpp-scFv ligand can clearly deliver exogenous genes selectively to the tumor *in vivo*. These results demonstrate the potential of this new way of efficiently targeting systemically delivered, cationic liposome complexes specifically to tumors *in vivo*.

30

Example 8

Construction and Purification of TfRscFv with a 3' Cysteine for Use in the Conjugation Method

In the absence of a lipid tag, another method was devised to attach the purified TfRscFv

5   protein to the lipoplex. This approach entails the conjugation of the single chain protein to cationic liposomes via a reducible group such as a sulfhydryl group. In the preferred embodiment a cysteine residue is added at the 3' end of the TfRscFv protein. Reduction of this cysteine results in a free sulfhydryl group which is capable of being conjugated to cationic liposomes, thus targeting the lipoplex to cells expressing the transferrin receptor. While the following examples

10   use cysteine as the reducible group it is obvious that other similar reducing groups would also work with this method.

1. Construction

A. Construction of an Expression Vector Containing a 3' Cysteine with a Histidine Tag for Use

15   in the Conjugation Method of Producing TfRscFv Immunoliposomes

As in Example 1, the VH-linker-Vκ scFv for the TfR was obtained from plasmid expression vector, pDFH2T-vecOK (described in Example 1). Using a 5' primer (5' GGCCCATGGAGGTGC AGCTGGTGG 3' (SEQ ID NO:3)) for PCR amplification, an *Nco*I site was introduced into pDFH2T-vecOK. The nucleotide sequence for the cysteine residue as

20   well as a *Not*I restriction site was introduced using a 3' primer (5' GGCGCGGCCGCGCATTTTATCTCCAGCTTG 3' (SEQ ID NO:4)). The PCR product was cloned into *Nco*I and *Not*I sites of the commercial vector pET26b(+) (Novagen). This vector also contains, 5' of the *Nco*I site, the pelB leader signal sequence. The presence of this sequence in the expression vector allows transport of the protein to the periplasmic space. To aid in

25   purification of the protein, the pET26b(+) vector also contains a Histidine tag sequence 3' of the *Not*I site (Figure 5).

B. Construction of an Expression Vector Containing a 3' Cysteine without a Histidine Tag for Use in the Conjugation Method of Producing TfRscFv Immunoliposomes

For human use as a therapeutic delivery vehicle, it is preferable that the TfRscFv be

30   produced without the Histidine tag. Therefore, the construct described in Example 8, section 1. A, was modified to eliminate this tag in the final protein product. To accomplish this, the same

5' primer as described above (in Example 8, section 1. A) was used. However, a different 3' primer was used. In addition to the nucleotide sequence for the cysteine residue and the *Not*I restriction site, this primer (5'GGCGCGGCCGCTCAGCATTTTATCTCCAGCTTG 3' (SEQ ID NO:5)), introduced a DNA stop codon adjacent to the cysteine sequence and before the *Not*I

5   site (Figure 6). Thus, the protein product of this construct will not contain the His-tag.

C. Construction of an Expression Vector Containing a 3' Cysteine with a 5'CBD™-Tag for Use in the Conjugation Method of Producing TfRscFv Immunoliposomes

A third alternative construct containing a cysteine residue for linkage to the cationic lipoplex using the conjugation method was also made. For this construct (Figure 7), the same

10   two primers described above in Example 8, section 1. B, were used. Thus no His-tag would be present in the protein product. However, the PCR product of these reactions was cloned into a different vector, pET37b(+) (Novagen). This vector contains a cellulose binding domain tag (CBD™-tag) and an S-tag, both 5' of the *Nco*I site in the vector. The CBD-tag sequence encodes a cellulose binding domain derived from a microbial cellulase. Thus, the presence of this tag

15   enables the use of cellulose-based supports for highly specific, low cost affinity purification of the protein product. The presence of the S-tag present in this construct allows for easy detection of the protein product on Western blots and for easy enzymatic quantitation of protein amounts.

2. Purification of the TfRscFv containing the Cysteine Residue

20   The commercially available *E. coli* expression host BL21(DE3), which contains the expressed lac repressor, was transformed with an expression vector (all three were used individually) described above in Example 8, section 1. A number of clones were selected and the ones that produced the best yield of TfRscFv were chosen. Purification of the protein from the construct described above in Example 8, section 1. A, with the histidine tag is given in detail

25   as an example, although the same method is used for purification of the cysteine containing TfRscFv protein from all three constructs described in Example 8, section 1. The majority of the TfRscFv protein (approximately 90%) was found not to be soluble but to be contained within the inclusion bodies. Therefore, the TfRscFv containing the cysteine-linker was purified from the inclusion bodies as follows. A single clone was inoculated into 5-10 ml LB containing 50 µg/ml

30   Kanamycin, and grown at 37°C, and 250 rpm to an OD_{600} of 0.5–0.7 (4-5 hrs). 30 ml of the mini culture was pelleted, suspended in LB broth, added to 1 L LB containing 50 µg/ml Kanamycin

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and incubated at 37°C and 250 rpm, to an OD_{600} of 0.5–0.7 (4-5 hrs). To induce expression of the TfRscFv protein, IPTG at a final concentration of 1 mM was added to the culture at this time and incubation continued for an additional 4 hrs. This time was determined to yield the maximum level of protein expression. The bacterial cultures were then collected by

5   centrifugation and lysed in 100 ml of cold 20 mM Tris-HCl, pH 7.5, containing 100 µg/ml lysozyme, at 30°C for 15 minutes. The sample was sonicated at 10 watts for 5 minutes (in 30 second bursts) with cooling on ice. The inclusion bodies were isolated by centrifugation at 13,000 g for 15 minutes. The resulting pellet was washed three times in cold 20 mM Tris-HCl buffer, pH 7.5. The purity and quantity of the inclusion bodies were determined by SDS-

10   polyacrylamide gel electrophoresis before solubilization.

The isolated inclusion bodies were dissolved in 100 mM Tris-HCl, pH 8.0 containing 6 M guanidine-HCl and 200 mM NaCl (6 M GuHCl buffer) and centrifuged at 12,300 g for 15 minutes to remove insoluble debris. 2-mercaptoethanol was added to the supernatant to a final concentration equal to approximately 50 molar fold of the protein concentration and the mixture

15   incubated with rotation for 1 hour at room temperature. The presence of such a high concentration of guanidine-HCl and the reducing agent results in a totally unfolded protein. Refolding of the TfRscFv protein was accomplished by dialysis at 4°C against decreasing concentrations of guanidine-HCl in the absence of 2-mercaptoethanol. Dialysis was performed for 24 hours each against the following concentrations of guanidine-HCl in 100 mM Tris-HCl,

20   pH 8.0 and 200 mM NaCl: 6 M, 3 M, 2 M, 1 M and 0.5 M. The last dialysis was against three changes of just 100 mM Tris-HCl, pH 8.0 and 200 mM NaCl. The fourth dialysis solution (of 1 M guanidine-HCl) also contained 2 mM glutathione (oxidized form) and 500 mM L-arginine. These reagents allow the partially refolded protein to form the proper disulfide bonds to produce the correct protein conformation. The solution was clarified by centrifugation at 13000 g to

25   remove aggregates. The sample was concentrated approximately 1.5 fold using the Centrplus centrifugal filter (Amicon) at 3000 g for 90 min. SDS-PAGE showed a single band of the solubilized cysteine containing TfRscFv with a molecular weight of approximately 28-30 kDa containing only minor contaminants (Figure 8).

30

Example 9

Preparation of scFv-liposomes by the Conjugation Method

1. Reduction of scFv

The purified TfRscFv was reduced by DTT to obtain monomer scFv-SH as follows: To scFv in HBS (10 mM HEPES, 150 mM NaCl, pH 7.4) was added 1 M DTT to a final concentration of 1-50 mM. After rotation at room temperature for 5-10 min, the protein was desalted on a 10-DG column (Bio-Rad). The free -SH group was measured by 5,5'-dithiobis-(2-nitrobenzoic acid) (DTNB, Ellman's reagent) (G.L. Ellman (1959) *Arch. Biochem. Biophys.* **82**:70-77. P.W. Riddles, R.L. Blakeley, B. Zeruer (1993) *Methods Enzymol.* **91**:49-60) and calculated as -SH/protein molar ratio, or number of free -SH per scFv molecule (Table 7). The results indicate that 1-10 mM DTT is appropriate for the scFv reduction.

Table 7

Reduction of TfRscFv

DTT Concentration (mM)	-SH/scFv molar ratio
0	0.15
1	0.45
10	1.94
20	2.26
50	3.03

2. Liposome Preparation

4-(*p*-maleimidophenyl)butyrate-DOPE (MPB-DOPE) (Avanti Polar Lipids) is included in the seven liposome formulations described in Example 3, to a 5-8% molar of total lipids. The MPB-liposomes were prepared the same way as described in Example 3. Other liposome preparation methods can also be used to prepare the cationic liposomes. For example, the ethanol injection method modified from that described by Campbell MJ (*Biotechniques* 1995 Jun; **18(6)**:1027-32) was used successfully in the present invention. In brief, all lipids were solubilized in ethanol and mixed, injected into vortexing pure water of 50-60 °C with a Hamilton syringe. The solution was vortexed for a further 10-15 min. The final concentration was 1-2 mM total lipids. The ethanol injection method is faster, easier and more robust. 1 M HEPES, pH 7.5 (pH 7.0-8.0) was added to a final concentration of 10-20 mM. Since we have found that the

maleimide group is not stable in aqueous solution with pH>7, the liposomes should be prepared in water (pH 5-6.5). The pH can be adjusted to 7.0-8.0 before linking to scFv-SH with 1 M HEPES buffer, pH 7.0-8.0, to facilitate the post-coating reaction.

3. Preparation of scFv-liposome-DNA Complexes

        A. Pre-linking Method

        scFv-SH was added to MPB-liposome at a protein/lipid (w/w) ratio of 1/5-1/40, preferably 1/10-1/20. The solution was mixed by gentle rotation for 30 min at room temperature to yield scFv-Lip. The scFv-Lip was used without purification although it can be purified by Sepharose CL-4B column chromatography. Plasmid DNA was diluted in water and added to the scFv-Lip at a DNA/lipid (μg/nmol) ratio of 1/6-1/20, preferably 1/10-1/14. The solution was mixed well for 5-15 min by inversion several times to produce scFv-Lip-DNA complex. scFv-Lip-DNA was used without purification although it can be purified by Sepharose CL-4B column chromatography. 80-100% of the scFv was found to be conjugated to the liposome.

        B. Post-linking Method

        Plasmid DNA was diluted in water and was added to the MPB-liposome at a DNA/lipid (μg/nmol) ratio of 1/6-1/20, preferably 1/10-1/14. The solution was mixed well for 5-15 min by inversion several times to produce an MPB-Lip-DNA complex. scFv-SH was then added to the complex at a protein/lipid (w/w) ratio of 1/5-1/40, preferably 1/10-1/20. The solution was mixed by gentle rotation for 30 min at room temperature, to produce the final scFv-Lip-DNA complex. The scFv-Lip-DNA was used without purification although it can be purified by Sepharose CL-4B column chromatography. 80-100% of the scFv was found to be conjugated to the liposome.

4. For intravenous injection, a 50% dextrose solution was added to the scFv-Lip-DNA to a final concentration of 5%.

<u>Example 10</u>

<u>Immunoreactivity of Cysteine Containing TfRscFv-</u>

<u>Immunoliposomes by the ELISA Assay</u>

        This example provides the characterization of the anti-TfRscFv-immunoliposomes produced by the conjugation method of this invention with respect to their ability to bind to TfR(+) cells *in vitro*. Human squamous cell carcinoma of head and neck cell line JSQ-3 served as the TfR(+) target cells for these studies.

As previously described in Example 4, indirect cellular enzyme-linked immunosorbent assay (ELISA) was employed to determine the immunoreactivity of the TfRscFv before and after conjugation to liposomes. Confluent JSQ-3 cells in 96-well plates were fixed with 0.5% glutaraldehyde in PBS for 10 min at room temperature. The plate was blocked with 5% fetal

5   bovine serum (FBS) in PBS at 30°C for 30 min. The cysteine containing TfRscFv alone, this TfRscFv conjugated to cationic liposomes (TfRscFv-immunoliposomes) and untargeted liposomes were added to wells in triplicate. An anti-transferrin receptor monoclonal antibody (Hb21, obtained from David Fitzgerald, NIH) was used in one series of wells as a positive control. The plate was incubated at 4°C overnight. The wells were washed three times with

10   PBS, and an anti-His monoclonal antibody (Qiagen) was added to each well (except for those receiving the antibody positive control) in 3% FBS in PBS and incubated at 37°C for 60 min. After three PBS washes, HRP-labeled goat-anti-mouse IgG (Sigma) diluted in 3% FBS was added to each well and incubated for 30 min at 37°C. The plate was washed three times with PBS and 100 µl substrate 0.4 mg/ml OPD in citrate phosphate buffer (Sigma) was added to each

15   well. The color-development was stopped by adding 100 µl 2 M sulfuric acid to each well. The plate was read on an ELISA plate reader (Molecular Devices Corp.) at 490 nm.

Indirect cellular ELISA clearly demonstrated that the anti-TfR scFv containing a C-terminal cysteine maintained its immunoreactivity. The OD_{490} values increased with increasing amounts of TfRscFv protein, rising from 0.060 ± 0.0035 with 0.6 µg of protein, to 0.100 ±

20   0.0038 at 1.5 µg and 0.132 ± 0.0031 with 3 µg of TfRscFv. Moreover, this TfRscFv protein appears to have even greater binding activity than the parental Hb21 anti-transferrin receptor antibody used as a positive control. The OD_{490} for the highest concentration of the Hb21 (100 µl) was approximately 2-4 fold less (0.033 ± 0.0086).

The indirect cellular ELISA assay was also performed after the same TfRscFv protein was

25   incorporated via the conjugation method of the invention (Example 9) into two different liposome complexes (Lip(A) and Lip(B)) to demonstrate the universality of this method with cationic liposomes. Both the pre- and post-linking conjugation methods of liposome preparation detailed in Example 9 were used. As shown in Table 8, the immunoreactivity of the TfRscFv prepared by the conjugation method is not lost through complexing to either of the two liposome

30   compositions. This was true for both pre- and post-linking methods used to produce the immunoliposome complex. The TfRscFv-targeted lipoplexes also demonstrated binding to the

23

cells. This binding was significantly higher than that of the liposome without the TfRscFv, suggesting that this binding is in fact mediated through the attachment of the TfRscFv to the transferrin receptor on the cells.

5   Table 8

Binding of TfRscFv-immunoliposomes Prepared by the

Conjugation Method to JSQ-3 Cells *In Vitro**

	DNA:Lipid Ratio	OD_{490}
Lip(B)-DNA	1:10	0.088
TfRscFv-Lip(A)-DNA by Pre-	1:10	0.152 ± 0.016
TfRscFv-Lip(A)-DNA by Pre-	1:12	0.166 ± 0.009
TfRscFv-Lip(A)-DNA by Post-	1:12	0.168 ± 0.006
TfRscFv-Lip(B)-DNA by Pre-	1:12	0.139 ± 0.012
TfRscFv only	--	0.235

* ELISA, OD_{490}, Mean $\pm$ SD (triplicate readings except for Lip(B)-DNA)
Pre- = Pre-linking Conjugation Method
Post- = Post-linking Conjugation Method

Example 11

Conjugated TfRscFv-immunoliposome Mediated Gene Transfection of Target Cells *In Vitro*

We determined the *in vitro* transfection efficiency of the TfRscFv-liposome complex, prepared by the conjugation method, in cells using the plasmid pLuc, which contains the firefly luciferase gene under control of the CMV promoter as the reporter gene. To demonstrate the universality of the TfRscFv as a targeting ligand, here also, as in Example 10, two separate liposome compositions (Lip(A) and Lip(B)) were conjugated to the TfRscFv protein. Human breast cancer cell line MDA-MB-435 and human squamous cell carcinoma of the head and neck cell line JSQ-3 were used in these studies. The *in vitro* transfection was performed in 24-well plates (Xu L, et al., *Hum. Gene Ther.* (1999) **10**:2941-2952). The transfection solutions were added to the cells in the presence of 10% serum. 24 hr later the cells were washed and lysed to measure the luciferase activity and protein concentration. The results are expressed as 10^3 relative light units (RLU) per µg protein in the lysate, as shown in Tables 9A and 9B.

Table 9A
Conjugated TfRscFv-immunoliposome Mediated Transfection *In Vitro*[a]

	Luciferase Activity (x 10^3 RLU/µg protein)	
	MDA-MB-435	JSQ-3
LipA	106	377
Tf-LipA	284	640
scFv-LipA*	560	1160
scFv-LipA**	660	1210
scFv-LipA (1/10)[@]	--	1315
scFv-LipA (1/20)[@]	--	751

\# Mean of duplicates
* Containing 5% MPB-DOPE
** Containing 7% MPB-DOPE
[@] Ratio of scFv/lipids (w/w)

Table 9B

In Vitro Transfection Activity of Conjugated TfRscFv-Immunoliposome-DNA Complexes

Prepared for Systemic Administration

	Luciferase Activity (x10^3 RLU/µg protein)	
	MDA-MB-435	JSQ-3
scFv-LipA-pLuc (pre-linking)*	58.4	675
scFv-LipA-pLuc (pre-linking)**	45.6	513
scFv-LipB-pLuc (pre-linking)*	51.4	415
scFv-LipA-pLuc (post-linking)*	58.1	856
scFv-LipA-pLuc (post-linking)**	45.3	343
scFv-LipB-pLuc (post-linking)*	47.2	237

* Containing 5% MPB-DOPE

** Containing 7% MPB-DOPE

The results show that the cysteine containing TfRscFv-immunoliposomes prepared by the conjugation method have very high transfection activity in vitro, 3-6 fold higher than the untargeted liposomes and 2-3 fold higher than the transferrin-targeted liposomes. This was true

for both liposome compositions and both human tumor cell lines. Thus, they still retain their immunoreactivity and can bind to their target receptor. Based upon Table 9A, the scFv-liposomes can also be used as efficient gene transfection reagents *in vitro*, and are much more efficient than commercially available cationic liposomes (DOTAP/DOPE and DDAB/DOPE) and transferrin-liposomes. The TfRscFv-immunoliposomes disclosed in the present invention can be used for an efficient *in vitro* gene transfection kit useful for the transfection of mammalian cells with transferrin receptors.

The TfRscFv is a smaller molecule than transferrin itself. Thus, the resulting complex is more compact and more easily taken up by the cells giving a higher transfection efficiency. These results are also advantageous for the use of the TfRscFv immunoliposome for systemic delivery for human use. The smaller size allows increased access to the tumor cells through the small capillaries. Most significantly, the TfRscFv is not a human blood product as is the Tf molecule. Therefore, the concerns and technical problems associated with the use of transferrin itself for human therapy are avoided.

Example 12
Conjugated TfRscFv-immunoliposome Mediated Expression of Wild-type p53 in a Nude Mouse Xenograft Model Following Systemic Delivery

In this example the ability of the TfRscFv, produced by the conjugation method of this invention, to direct a lipoplex carrying the wild-type p53 (wtp53) gene preferentially to tumor cells *in vivo* after systemic delivery is demonstrated. To demonstrate the universality of the TfRscFv as a targeting ligand, here also, as in Example 10, two separate liposome compositions (Lip(A) and Lip(B)) were complexed to the cysteine-containing TfRscFv protein by the conjugation method. Only the pre-linking method of conjugation as detailed in Example 9 was used in this study. 2.5×10^6 MDA-MB-435 human breast cancer cells were subcutaneously injected into 4-6 wk old female athymic nude mice. 1.1×10^7 DU145 human prostate cancer cells suspended in Matrigel® collagen basement membrane (Collaborative Biomedical Products) were also subcutaneously injected into 4-6 week old female athymic nude mice and tumors were allowed to develop. Animals bearing tumors of between 50-200 mm^3 were used in the study (1 animal/sample tested). Conjugated TfRscFv immunoliposomes carrying the wtp53 gene, as well as untargeted Lip(B)-p53 and wtp53 naked DNA were intravenously injected into the tail vein

of the animals.   As an additional control, conjugated TfRscFv-Lip(A) carrying the empty vector in place of the p53 containing vector was also injected into a mouse.   As described in Example 7, approximately 60 hours post-injection, the animals were sacrificed and the tumors, as well as the liver, were excised.   Protein was isolated from the tissues and 100 µg of each sample (as determined by protein concentration assay) was run on a 10% polyacrylamide gel for Western blot analysis using an anti-p53 monoclonal antibody.   In both of these tumor types the endogenous mouse and the exogenous human p53 migrate at the same position.   The results here mirror those described in Example 7.   As shown in Figure 9, both the DU145 and MDA-MB-435 tumors from the animals intravenously injected with the TfRscFv-Lip(A)-pCMVp53 lipoplex or the TfRscFv-Lip(B)-pCMVp53 lipoplex prepared by the conjugation method displayed a high level of expression of exogenous wtp53, as indicated by the intense p53 signal and an additional lower band, with the best expression in the DU145 tumors.   While it appears that in both tumor types the Lip(A) composition was somewhat better than the Lip(B), both liposome compositions worked demonstrating the universality of this method.   Only the endogenous mouse p53 protein was evident in the liver of these animals.   In contrast, only the endogenous mouse p53 protein was evident in the tumors excised from the mice injected with the conjugated TfRscFv-Lip(B) carrying the empty vector or the naked wtp53 DNA.   A small increase in p53 expression also was observed in the DU145 tumor with the untargeted Lip(B)-p53.   Thus, the conjugated TfRscFv-immunoliposomes delivered the wtp53 gene preferentially to the tumors, as desired.   It is also significant that this tumor targeting was evident in two different tumor types, indicating the general usefulness of the method of this invention.   Therefore, the methods of this invention described in the preceding Examples generate a TfRscFv protein that not only retains its ability to bind to cationic liposomes but is still immunologically active preserving its ability to bind to the transferrin receptor *in vitro* and *in vivo*, thus fulfilling our objective of producing a tumor-specific, targeted immunoliposome for gene therapy.

While the invention has been disclosed in this patent application by reference to the details of preferred embodiments of the invention, it is to be understood that the disclosure is intended in an illustrative rather than in a limiting sense, as it is contemplated that modifications will readily occur to those skilled in the art, within the spirit of the invention and the scope of the appended claims.

WHAT IS CLAIMED IS:

1.   An immunoliposome comprising i) a cationic liposome, ii) an antibody or antibody fragment, and iii) a nucleic acid.

2.   The immunoliposome of claim 1 wherein said antibody or antibody fragment is capable of binding to a transferrin receptor.

3.   The immunoliposome of claim 1 wherein said nucleic acid is DNA.

4.   The immunoliposome of claim 1 wherein said nucleic acid encodes a wild type p53.

5.   The immunoliposome of claim 1 wherein said antibody or antibody fragment comprises a lipid tag.

6.   The immunoliposome of claim 1 wherein said antibody or antibody fragment is covalently bound to said cationic liposome via a sulfur atom which was part of a sulfhydryl group at a carboxy terminus on said antibody or antibody fragment.

7.   The immunoliposome of claim 6 wherein said sulfur atom is part of a cysteine residue.

8.   The immunoliposome of claim 6 wherein said antibody or antibody fragment is covalently bound to DOPE linked to MPB or other sulfhydryl reacting group.

9.   The immunoliposome of claim 1 wherein said antibody fragment is a single chain.

10.   The immunoliposome of claim 1 wherein said antibody or antibody fragment and said cationic liposome are present at a protein:lipid ratio (w:w) in the range of 1:5 to 1:40.

11.   The immunoliposome of claim 1 wherein said nucleic acid and said cationic liposome are present at a nucleic acid:lipid (μg:nmol) ratio in the range of 1:6 to 1:20.

12.   A pharmaceutical composition comprising the immunoliposome of claim 1.

13.   A method of preparing a nucleic acid-cationic immunoliposome complex comprising the steps of:

a) mixing nucleic acid encoding a wild type p53 with a cationic liposome to produce a nucleic acid-liposome complex;

b) preparing an antibody or antibody fragment capable of binding to a transferrin receptor; and

c) mixing said nucleic acid-liposome complex with said antibody or antibody fragment to form said nucleic acid-cationic immunoliposome complex.

14.   The method of claim 13 wherein said antibody or antibody fragment comprises a lipid tag.

15.   The method of claim 13 wherein said antibody or antibody fragment comprises a reducible group at a carboxy terminus prior to mixing with said nucleic acid-liposome complex.

16.   The method of claim 15 wherein said reducible group is a sulfhydryl.

17.   The method of claim 16 wherein said sulfhydryl is part of a cysteine residue.

18.   The method of claim 15 wherein said cationic liposome comprises DOPE linked to MPB or other sulfhydryl reacting group.

19.   The method of claim 13 wherein said nucleic acid is DNA.

20.   The method of claim 13 wherein said antibody or antibody fragment and said cationic liposome are present in said nucleic acid-cationic immunoliposome complex at a protein:lipid ratio (w:w) in the range of 1:5 to 1:40.

21.   The method of claim 13 wherein said nucleic acid and said cationic liposome are present in said nucleic acid-cationic immunoliposome complex at a nucleic acid:lipid (μg:nmol) ratio in the range of 1:6 to 1:20.

22.   The method of claim 13 wherein said antibody fragment is a single chain.

23.   A method of preparing a nucleic acid-cationic immunoliposome complex comprising the steps of:

a) preparing an antibody or antibody fragment capable of binding to a transferrin receptor;

b) mixing said antibody or antibody fragment with a cationic liposome to form a cationic immunoliposome; and

c) mixing said cationic immunoliposome with nucleic acid encoding a wild type p53 to form said nucleic acid-cationic immunoliposome complex.

24.   The method of claim 23 wherein said antibody or antibody fragment comprises a lipid tag.

25.   The method of claim 23 wherein said antibody or antibody fragment comprises a reducible group at a carboxy terminus prior to mixing with said nucleic acid-liposome complex.

26.   The method of claim 25 wherein said reducible group is a sulfhydryl.

27.   The method of claim 26 wherein said sulfhydryl is part of a cysteine residue.

28   The method of claim 25 wherein said cationic liposome comprises MPB-DOPE.

29.   The method of claim 23 wherein said nucleic acid is DNA.

30.   The method of claim 23 wherein said antibody or antibody fragment and said cationic liposome are present in said nucleic acid-cationic immunoliposome complex at a protein:lipid ratio (w:w) in the range of 1:5 to 1:40.

31.   The method of claim 23 wherein said nucleic acid and said cationic liposome are present in said nucleic acid-cationic immunoliposome complex at a nucleic acid:lipid (μg:nmol) ratio in the range of 1:6 to 1:20.

32.   The method of claim 23 wherein said antibody fragment is a single chain.

33.   A method for providing a therapeutic molecule to an animal in need thereof, comprising administering to said animal a therapeutically effective amount of a nucleic acid-cationic immunoliposome complex comprising i) a cationic liposome, ii) an antibody or antibody fragment, and iii) a nucleic acid.

34.   The method of claim 33 wherein said complex is administered systemically.

35.   The method of claim 33 wherein said complex is administered intravenously.

36.   The method of claim 33 wherein said antibody or antibody fragment is capable of binding to a transferrin receptor.

37.   The method of claim 33 wherein said antibody fragment is a single chain.

38.   The method of claim 33 wherein said nucleic acid is DNA.

39.   The method of claim 33 wherein said nucleic acid encodes a wild type p53.

40.   The method of claim 33 wherein said antibody or antibody fragment comprises a lipid tag.

41. The method of claim 33 wherein said antibody or antibody fragment is covalently bound to said cationic liposome via a sulfur atom which was part of a reducible group at a carboxy terminus on said antibody or antibody fragment.

42. The method of claim 41 wherein said reducible group is a sulfhydryl.

43. The method of claim 42 wherein said sulfhydryl is part of a cysteine residue.

44. The method of claim 41 wherein said antibody or antibody fragment is covalently bound to DOPE linked to MPB or other sulfhydryl reacting group.

45. The method according to claim 33 wherein said antibody or antibody fragment and said cationic liposome are present in said nucleic acid-cationic immunoliposome complex at a protein:lipid ratio (w:w) in the range of 1:5 to 1:40.

46. The method according to claim 33 wherein said nucleic acid and said cationic liposome are present in said nucleic acid-cationic immunoliposome complex at a nucleic acid:lipid (μg:nmol) ratio in the range of 1:6 to 1:20.

47. The method according to claim 33 wherein said animal is a human.

48. The method according to claim 33 wherein said animal has cancer.

49. The method according to claim 48 wherein said cancer is selected from the group consisting of i) head and neck cancer, ii) breast cancer and iii) prostate cancer.

50. A kit comprising a cationic immunoliposome wherein said cationic immunoliposome comprises a transferrin receptor binding antibody fragment.

51. The kit of claim 50 wherein said antibody fragment is a single chain.

52.   The kit of claim 50 wherein said antibody fragment comprises a lipid tag.

53.   The kit of claim 50 wherein said antibody fragment is conjugated to a cationic liposome.

54.   The kit of claim 50 said antibody fragment and cationic lipids are present in a protein:lipid ratio (w:w) in the range of 1:5 to 1:40.

55.   The kit of claim 50 wherein said cationic immunoliposome is in an aqueous solution.

56.   The kit of claim 50 further comprising a nucleic acid for use as a positive control in a container separate from said cationic immunoliposome.

57.   The kit of claim 56 wherein said nucleic acid encodes a reporter gene selected from the group consisting of luciferase, β-galactosidase and green fluorescent protein.
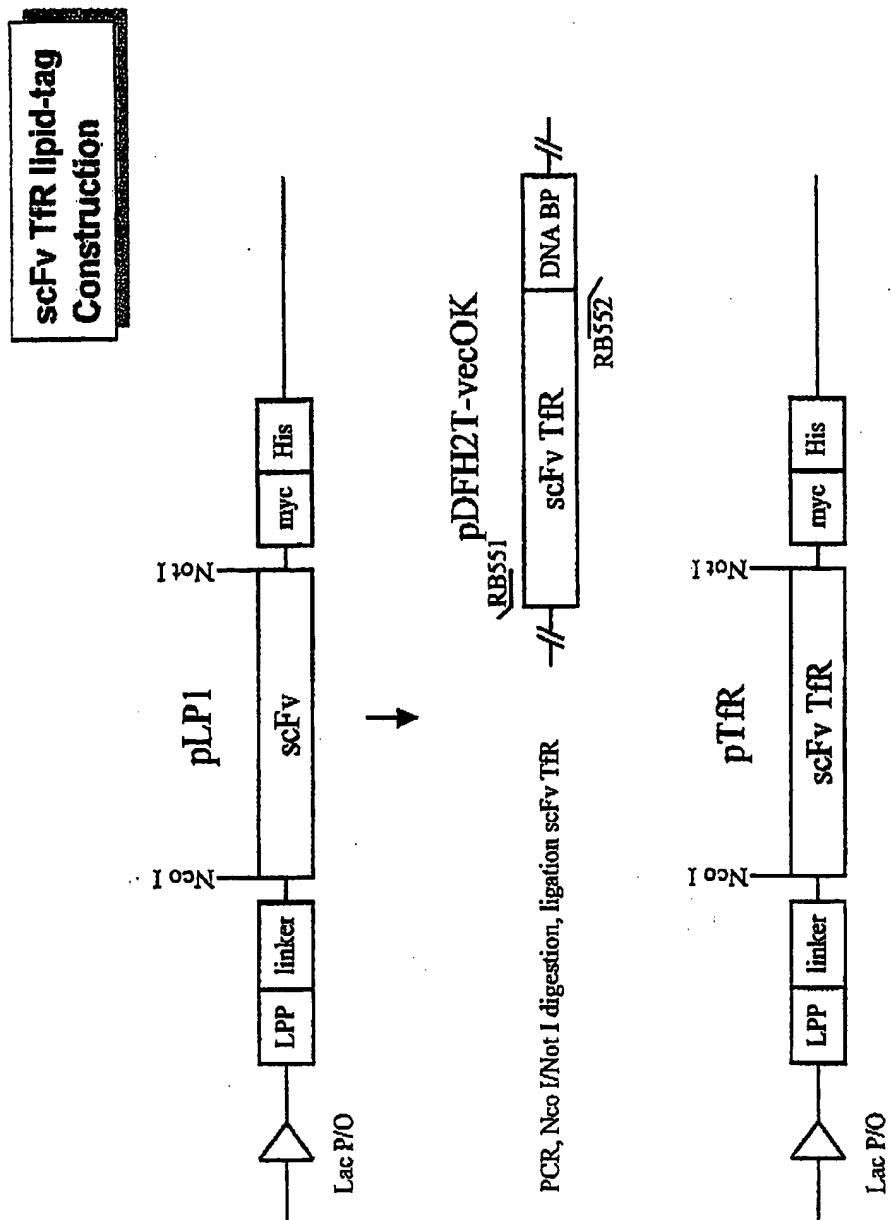
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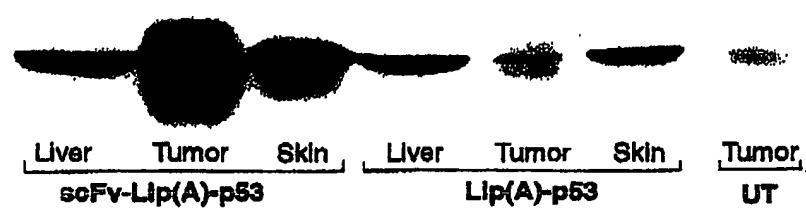
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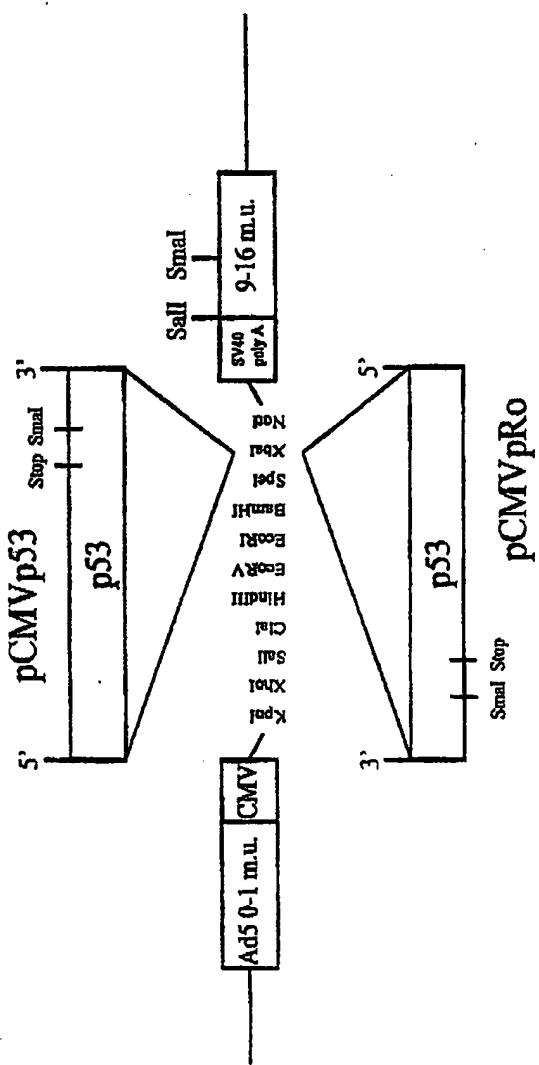
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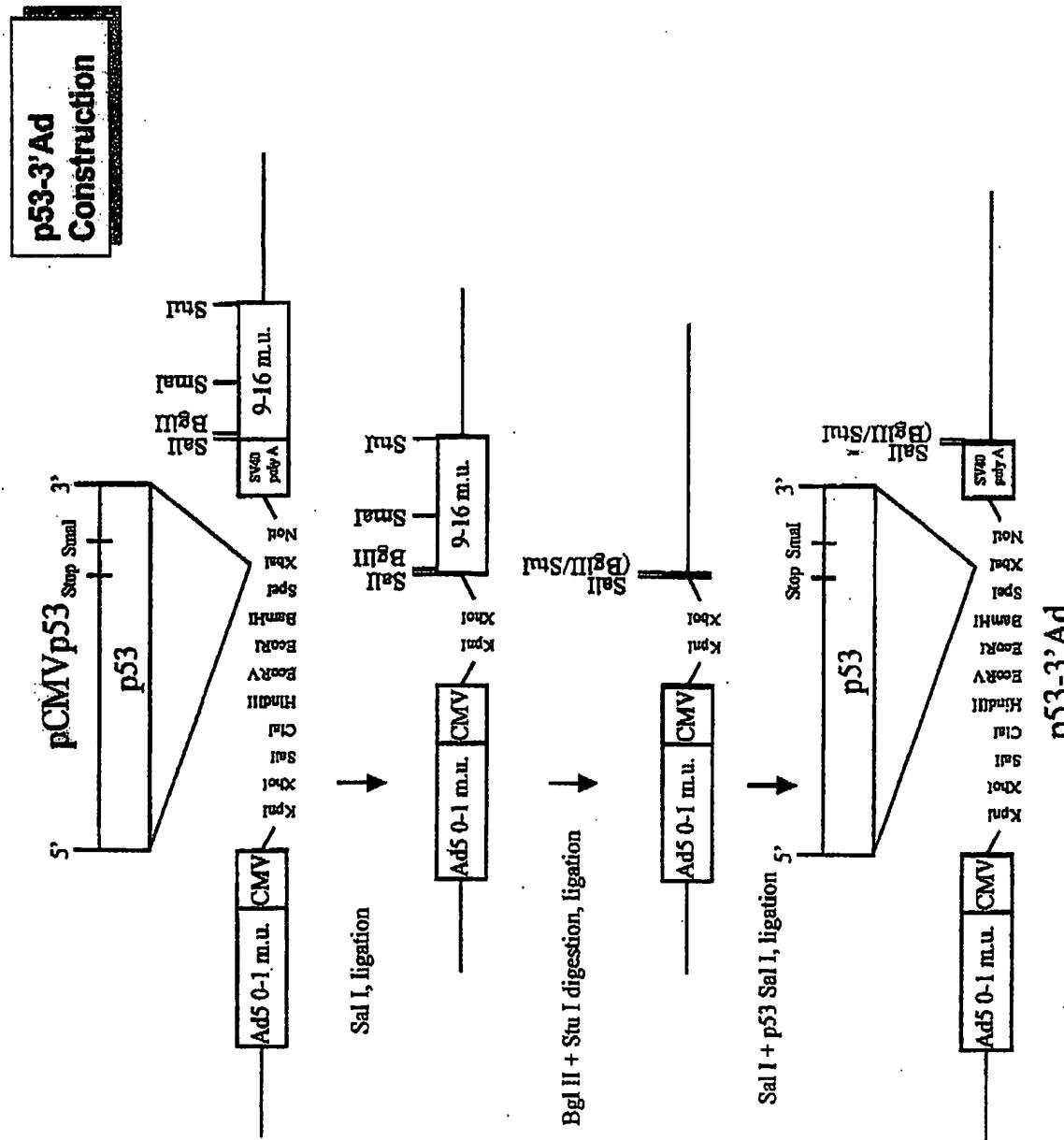
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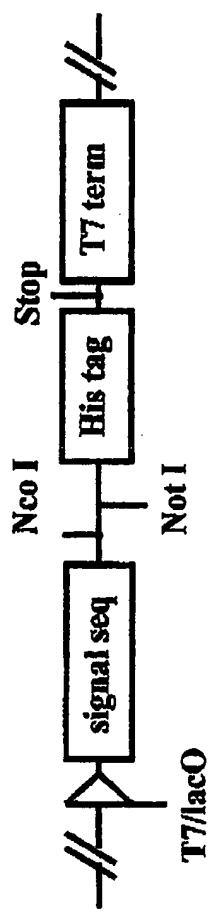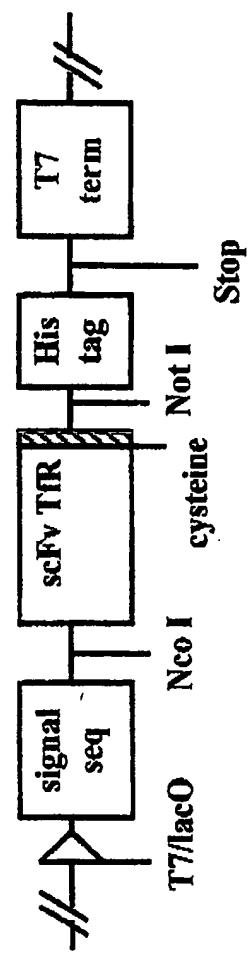
FIG. 5

FIG. 6

FIG. 7

FIG. 8

FIG. 9

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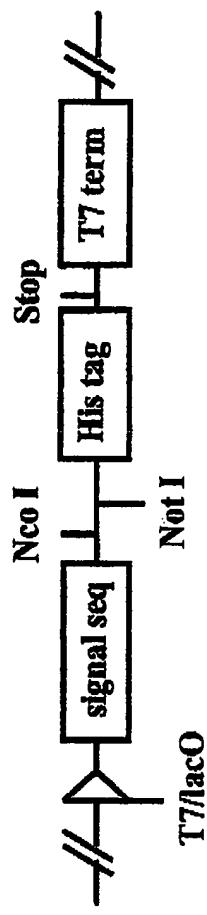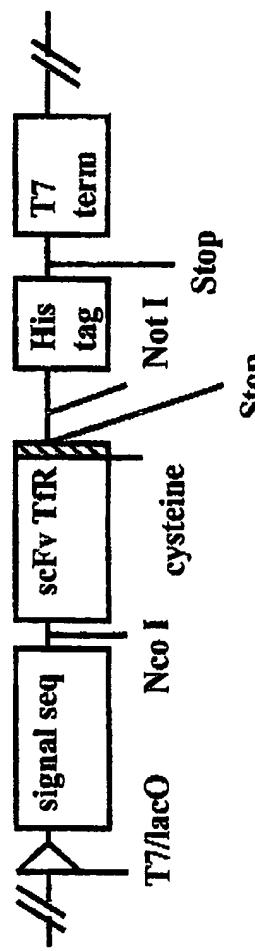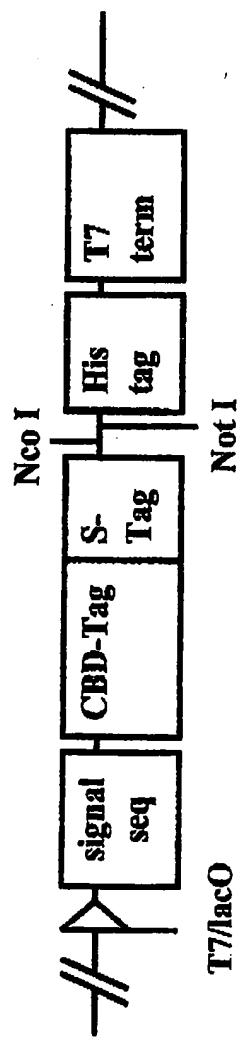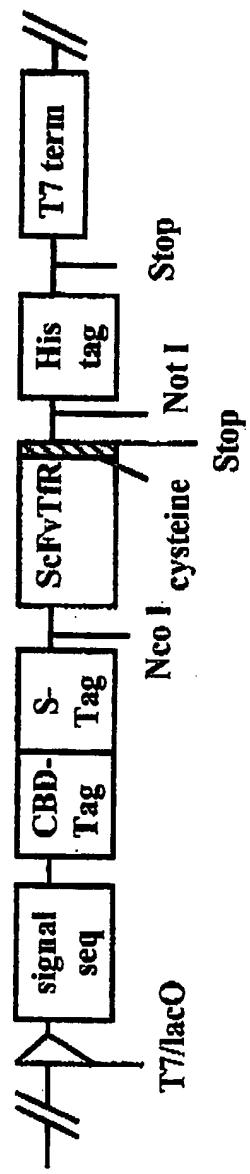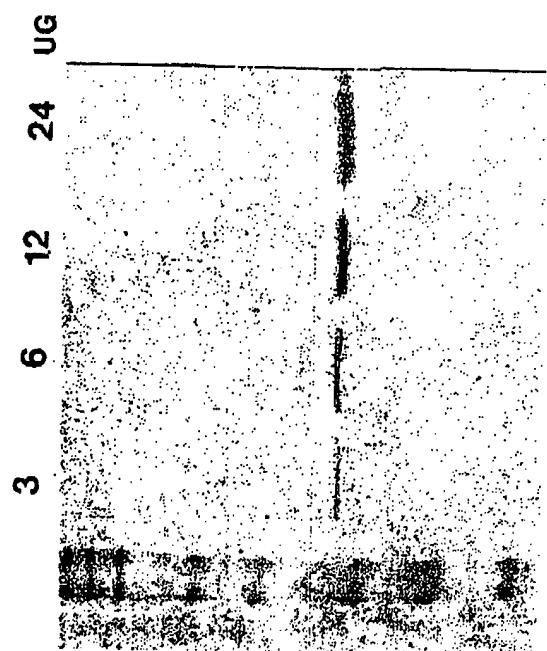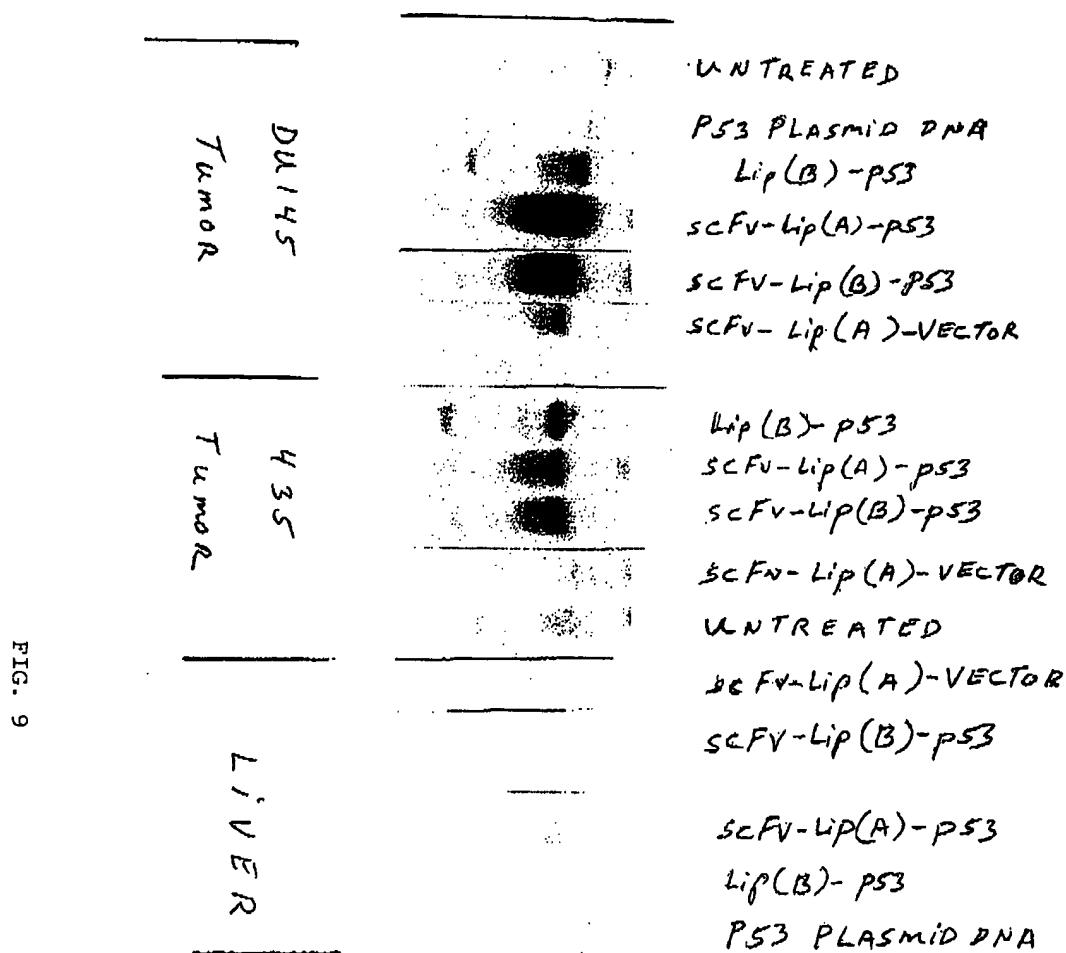
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